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CONFLICT RESOLUTION AND OPTIMIZATION OF MULTIPLE-SATELLITE SYSTEMS (CROMSAT)

by

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June 2007

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13. ABSTRACT (maximum 200 words)

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CONFLICT RESOLUTION AND OPTIMIZATION OF MULTIPLE-SATELLITE SYSTEMS (CROMSAT)

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ABSTRACT

This thesis produces models of satellite constellations using finite state automata (FSA) or finite automata (FA) and optimizes the sequence of targets for two missions. Two simplified FSA models of satellite constellations with one ground control station (GCS) are developed. The first model is of a single spacecraft and the second includes two spacecraft. Based upon the language, states, and state transitions of each model, the author transforms the FA into a network and enumerates the shortest paths for indicative lists of meta-tasks from each model. The first model is provisionally implemented in MATLAB. The author finds two separate optimal target selection sequences for randomly generated sample target sets using commercial off-the-shelf optimization software. Although stochastically fabricated, the sample target sets reflect valid scenarios for a satellite imagery mission. The first sequence, a traveling salesman problem, minimizes the time required for processing all targets given a multiple orbit mission. For a representative sample target set, this is 2.34 orbits. The second sequence, a prize collecting traveling salesman problem, maximizes the number of targets processed given a dual orbit mission. For the same sample target set, two orbits permit the processing of seven targets.

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EXECUTIVE SUMMARY

This thesis produces models of satellite constellations using finite state automata (FSA) or finite automata (FA) and optimizes the sequence of targets for two missions. Two simplified FSA models of satellite constellations with one ground control station (GCS) are developed. The first model is of a single spacecraft and the second includes two spacecraft. Based upon the language, states and state transitions of each model, the author transforms the FA into a network and enumerates the shortest paths for indicative lists of meta-tasks from each model. The first model is provisionally implemented in MATLAB. The author finds two separate optimal target selection sequences for randomly generated sample target sets using commercial off-the-shelf optimization software. Although stochastically fabricated, the sample target sets reflect valid scenarios for a satellite imagery mission. The first sequence, a traveling salesman problem, minimizes the time required for processing all targets given a multiple orbit mission. The second sequence, a prize collecting traveling salesman problem, maximizes the number of targets processed given a dual orbit mission.

An FA, or in some instances a finite state machine (FSM), is a model of behavior composed of a finite number of states, transitions between those states, and actions. By definition, the FA is in its start state upon receipt of a procedure's first input. Accept states are the subset of final states, which represent the successful execution of the modeled procedure. The transition function defines transitions between states that result from actions as detailed or specified in the procedure.

Formally, an FA, is denoted by a 5-tuple using the symbology:

$M = (Q, \Sigma, \delta, q_o, F)$, where:

M – finite state machine

Q – set of states

Σ – alphabet of symbols

q_o – start state

F – set of accept or final states

δ – transition function

The tabulated transition function is constructed from three components: the list of states in the leftmost column, the list of inputs in the topmost row excluding the first column, and a table of states that reflect the valid transitions for the input and state (read row and column) combinations. It reflects the language accepted by the FA.

The language L(M) of the FA M is the set of strings that can be derived from the start symbol, S, or start state, q_o, according to the description $M = (Q, \Sigma, \delta, q_o, F)$. The protocols that define which transitions are permitted, i.e. the rule set or transition function factor directly into the language generated by the parent entity. Hence for the case of an FA M, the formal symbolic description is:

$L(M) = \{\xi | \delta(q_o, \xi) \in F\}$, where:

q_o – start state

δ – transition function

F – set of accept or final states

σ– the elements of the alphabet, Σ

$\xi \subset \{\sigma\}$ – input strings composed from the elements of the alphabet

The author randomly generates eight target locations with corresponding dwell times. For test instances, the traveling salesmen problem and the prize collecting traveling salesmen problem each solve in less than one second using commercial off-the-shelf software.

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I. INTRODUCTION

This thesis produces models of satellite constellations using finite state automata (FSA) or finite automata (FA) and optimizes the sequence of targets for two missions. Two simplified FSA models of satellite constellations with one ground control station (GCS) are developed. The first model is of a single spacecraft and the second includes spacecraft. Based upon the language, states and state transitions of each model, the author transforms the FA into a network and enumerates the shortest paths for indicative lists of meta-tasks from each model. The first model is provisionally implemented in MATLAB (MATLAB, 2007). The author finds two separate optimal target selection sequences. The first, a traveling salesman problem, minimizes the time required for processing all targets given a multiple orbit mission. The second, a prize collecting traveling salesman problem, maximizes the number of targets processed given a dual orbit mission.

A. BACKGROUND

Satellite systems have been in orbit since the successful launch of Sputnik I on October 4, 1957. The complexity of the platforms and ground controls stations (GCS) has increased and expanded considerably since then. Commensurately the tasking has also developed. In terms of GCS personnel, the initial concept of a large team of operators allocated to a single spacecraft has now morphed into a distinctly contrasting situation where a multiple satellite system is now controlled/co-coordinated by a single operator or a very small team (Sekhavat, 2007). Given the adjustments of the workforce and the general increase in demand for satellite imagery products, the tasking of satellites or multiple satellite systems has become more complicated (Department of the Army, 2005 & 2006). As various related technologies are further honed and developed, the requirement for better management of the resource becomes even more imperative (Ross I.M., 2006).

Thus, a method for examining the tasking of multiple satellite systems aimed at resolving scheduling conflicts and optimizing both the task duration and the spacecraft lifetimes should provide insight into potential cost savings and improvements in the overall operation of the system.

B. DIRECTION OF RESEARCH

Potential future satellite systems will require greater distributed functionality for cooperative execution of meta-tasks. A meta-task for a system of satellites is analogous to a reconnaissance mission for ground troops. That is, clearly specified with a standardized but concise vocabulary; for example, “measure the distance to an approaching object" or “take pictures over 3° 07' S latitude, 152° 38' E longitude.” Conflict resolution and optimization of the scheduling and tasking of multiple satellites requires the identification of the appropriate system components (i.e., satellites) that yield the most suitable outcome. The optimal allocation of tasks is a considerable undertaking. The problem is well-known to be NP-hard (Cassandras & Lafortune, 1999).

There are various extant models, methods and procedures for the analysis of a satellite system. However, the author did not find the application of finite state machines or finite state automata for generating the models, methods and procedures for a satellite system as presented in this thesis. Finite state machines or automata are used extensively in the computer science, digital communications and electronic engineering fields (Cobleigh et al., 2002; Hennie, 1968). Employment beyond these fields has expanded since, but there remains an apparent dearth of universal appeal of finite automata for many applications.

II. FUNDAMENTALS

A. OUTLINE

In order to achieve the aim of this undertaking, the author considers three primary topics: space systems, finite automata (FA) and optimization models. Space systems is an expansive field and thus the author focuses directly at the specific problem under consideration. Where appropriate, the author made simplifications to prevent the degeneration of this problem into the pits of intractability. In addition, FA needs explanation and clarification in order to establish the foundational concepts upon which the models are constructed and where further research may be explored. Finally, the optimization models merit discussion too. Then, with the essential groundwork covered, the author specifies the particular research questions.

B. DISTRIBUTED SPACECRAFT SYSTEMS (DSS)

When considering the DSS it is necessary to clarify some of the specifics as they apply to this problem. Space systems are very detailed and have a vast array of constituent elements (Pisacane, 1994 & 2005). Grouping these into three primary fields, namely terrestrial concerns, vehicular issues and the operating environment, simplifies the discussion, permits a useful delineation between topics and provides focus on the essential elements without loss of generality.

1. Terrestrial Concerns

Terrestrial concerns are those matters which affect the construction of the model from an earthbound perspective. In particular, there are two primary concerns: the ground control station (GCS) and targets.

a. *Ground Control Station (GCS)*

In a DSS, the GCS plays a pivotal role. It is the central point through which all communications are transmitted to and received from the DSS. It monitors the status of each spacecraft in the DSS, either directly or remotely, and as the name suggests, it is the focal point of control of the DSS. The GCS determines orbit adjustments or realignments and transmits them to the relevant spacecraft. The GCS may also provide the facilities for initial processing of any imagery or data collection products. Additionally, the GCS may also conduct the assignment and scheduling of spacecraft to targets along with the production of the necessary telemetry and commands. For individual satellites, there are different blackout regions for respective GCSs. These blackout regions are predominantly a function of GCS location and orbit.

b. *Targets*

Targetry is a function of the payload. Payloads designed for communications relay, interception and/or monitoring are used for relevant exchanges. Whereas, in the case of a DSS in which the primary payload is for imagery, the tasking is more focused on pictorial or graphical observations and subsequent physical characteristic quantification. Designating targets with the conventional longitude and latitude referencing system provides an inherent baseline to Greenwich Mean Time (GMT).

2. Vehicular Issues

Referring to each spacecraft of a satellite system as a vehicle permits the use of a commonly understood vernacular. Vehicular issues can be classified into five distinct categories: design and purpose, tasks, launch, orbits and lifetimes and reliabilities.

a. Design & Purpose

The design of the satellites covers a very wide array of factors and inputs. One of the more influential is that of purpose because the purpose dictates the payload (Pisacane, 1994 & 2005). Specifically for this problem, the payload is an imagery package.

b. Tasks, Meta-tasks and Missions

The concept adopted for the development and analysis of the DSS tasking operations is one of sequential hierarchal complexity in conjunction with the state space of the FA. That is, the first level of operation is developed then the second is a superset of some of the combinations and permutations of the first. In addition, the same procedure applies to the second to produce the third.

Therefore, for the DSS the author uses the following approach. For an imagery satellite, the tasks are those actions that consist of some “universal” or repeated state changes. Meta-tasks are a collections of tasks that cause the spacecraft to cycle through a complete sequence of actions and ordinarily conclude with the spacecraft in an accept state. Missions are collections of meta-tasks, either with or without the transition, to an accept state between meta-tasks. Missions, likewise, conclude with the spacecraft in an accept state.

c. Launch

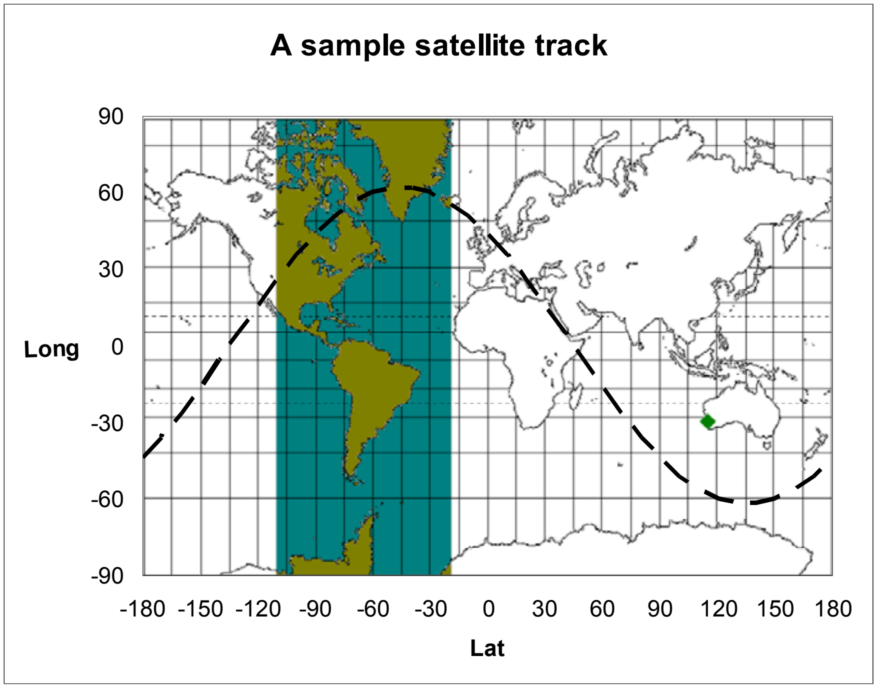
The launch of satellites is generally achieved in one of two methods. The satellite can either be directly put in orbit via conventional rocketry or it can be carried aloft in a secondary vehicle which then releases the satellite into orbit once the secondary vehicle has established a stable orbit itself. NASA has competently demonstrated both techniques of launching satellites into orbit.

d. Orbits

The maximum distance (apogee) of the satellite from the surface of the earth and the relative motion of the earth/satellite system is generally used to classify the orbits of artificial satellites. As the difference between the apogee and the point of closest approach (perigee) increases, the more elliptical the orbit becomes. Four common classifications of orbits are low Earth orbit (LEO), medium Earth orbit (MEO) or intermediate circular orbit (ICO), high Earth orbit (HEO) and geostationary orbit. An orbit may also be described by its Keplerian elements: inclination, longitude of the ascending node, argument of periapsis, eccentricity, semi-major axis and mean anomaly at epoch (Wikipedia, 2007).

In addition to these traditional set of elements there are several other relevant terms. These include nadir, zenith, dwell, orbit adjustment, orbit repair and track. Nadir is the astronomical term for the point in the sky directly below the observer, or more precisely, the point in the sky with an inclination of −90°, with zenith being the "antonym." Dwell refers to a period of time in which a specific point on the surface of the earth is the center of attention of some piece of imagery equipment on a satellite. The adjustment of an orbit means the intentional changing of the Keplerian elements to new values, whereas orbit repair is a restoration of the spacecraft's orbit from whatever its orbit has changed or degenerated into back to the original or predetermined and specified orbit. Finally, the track of an orbit is the path on the surface of the earth marked out by sequential nadir plotting of the satellite's position.

Figure 1 is a graphical representation of an example satellite track. Additionally it also displays a GCS with its indicative LEO blackout region.



NB: GCS location is indicated by the green diamond ◆

Figure 1. Indicative Satellite Track, with GCS & its LEO Black-out Region

e. Lifetimes and Reliability

When considering the degree of difficulty and cost to repair satellites post-launch, it is evident that all contributing factors to the lifetime and reliability are fully examined, explored, analyzed and where necessary, rectified prior to launch. Conducting extensive testing (burn-in, etc.) on all major components is an attempt to satisfy the reliability requirements. Additionally, redundancy is built into many systems to enhance the reliability and assist with extend lifetimes (Boddy et al., 2004; Pisacane, 1994 & 2005). Even so, there are cases where the satellites are still operating after the expiration of several operational lifetimes, albeit not at the original capacity, but operating to a degree that remains satisfactory. However, it is not standard procedure to rely upon the coaxing of extended operations from satellites to make up the original operation lifetime (Ross & Loomis, 2007).

3. Operating Environment

The operating environment for satellites is very harsh. In fact, it is exceptionally difficult to replicate such an environment on Earth. However, there is a large body of knowledge of the requirements for negating some of the detrimental environmental effects (Pisacane, 1994 & 2005). The operating environment directly affects the overall lifetime of the spacecraft (Wilson, 2001).

a. Earth Related Effects

Satellites in LEO, while still subject to atmospheric drag, detrimental gravitational effects and thermal cycling, have some degree of protection from the solar wind and solar flares afforded by the magnetosphere and Van Allen belt (SEC, 2007). Thus, the circuitry and electronic components of satellites in such orbits are subject to less environmental degradation (Ross A. & Loomis, 2007).

Man-made Earth related effects also need consideration. During times of peace, the environmental threats to satellites are from the thousands of pieces of space junk and debris in orbit (Meshishnek, 1995). However, in periods of hostilities, there exists the clear potential for a ground-based attack and/or denial of access to spacecraft (Wilson, 2001). On January 11, 2007, at 5:28 pm EST, the Peoples Republic of China (PRC) conducted its first successful direct ascent anti-satellite (ASAT) weapons test, launching a ballistic missile armed with a kinetic kill vehicle (not an exploding conventional or nuclear warhead) to destroy the PRC's Fengyun-1C weather satellite at about 530 miles up in LEO in space (Kan, 2007). More recently, Russia publicly claimed that the United States of America deliberately shot down one of their satellites, which is a claim that is vehemently and categorically denied by the alleged aggressor (Satnews, 2007). However, there are also other ground-based ways and means within the grasp of not so technically advanced entities that permit the temporary denial or disruption of spacecraft systems (Carlyle, 2006).

b. Helio Effects

In the case of higher orbits, the charge accumulation and heightened radiation exposure from the Sun can lead to reduced lifetimes and compromised reliability. Additionally, solar activity may be so intense that all satellites are subject to some amount of degradation regardless of orbit (Pisacane, 1994 & 2005; SEC, 2007).

4. Stochastic Markovian Analysis of Inoperability

Given comments above in regards to the threats to spacecraft operability and despite the vast amount of resources invested in ensuring high standards of reliability, there are various events that have the potential to cause spacecraft to become inoperable, either temporarily or permanently. Using standard procedures for the construction of Markov chains and some key assumptions about the state transitions of the finite automata, a transition probability matrix, **P**, may be developed (Ross S., 2003).

C. FINITE AUTOMATA (FA)

The finite automaton is a mathematical model of a system with discrete inputs and outputs, often with discrete time intervals. The system can be in any one of a finite number of internal configurations or "states." The state of a system summarizes the information concerning past inputs that is needed to determine the behavior of the system on subsequent inputs (Hopcroft & Ullman, 1979).

1. Types of Finite Automata (FA)

The term finite automaton, finite automata (FA) in plural, includes a wide range of related models including, but not limited to:

Deterministic finite automata (DFA),

Non-deterministic finite automata (NFA),

Two-way deterministic finite automata (2DFA),

Moore machines,

Mealy machines,

Deterministic pushdown automata (DPDA or PDA),

Non-deterministic pushdown automata (NPDA),

Turing machine (TM),

Non-deterministic Turing machine,

Multidimensional Turing machine,

Multi-head Turing machine, and

Off-line Turing machine, (Hennie, 1968; Hopcroft & Ullman, 1979).

The first of these is used in this thesis with some consideration given to the second. Both non-deterministic finite automata (NFA) and pushdown automata (PDA) models may provide some secondary utility. However, that is a topic for further research.

2. Definition of FA

A FA, or in some instances a finite state automata (FSA) or finite state machine (FSM), is a model of behavior composed of a finite number of states, transitions between those states, and actions. By definition, the FA is in its start state upon receipt of a procedure's first input. Accept states are the subset of final states, which represent the successful execution of the modeled procedure. The transition function defines transitions between states that result from actions as detailed or specified in the procedure, (Hopcroft & Ullman, 1979).

a. Transition Diagram

A graphical form of the transition function, namely the transition diagram, is a directed graph that is associated with the FA and can be seen in

Figure 2. The vertices (or nodes) of the graph correspond to the states of the FA. If there is a transition from the state "*q*" to the state "*p*" on input "*a*" then there is an arc labeled "*a*" from the state "*q*" to the state "*p*" in the transition diagram. This concept of an FA described by a directed graph indicates that some well-defined optimization routines and analyses may be relevant for this problem. The FA accepts a string "*x*" if the sequence of transitions corresponding to the symbols of "*x*" leads from the start state to an accepting state (Hopcroft & Ullman, 1979).

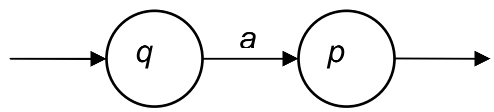


Figure 2. Example of a Graphical Transition Diagram (After Hennie, 1968; Hopcroft & Ullman, 1979)

b. Languages and Grammars

The actions are the language of the FA and are composed from the alphabet of inputs, i.e., sequences of transitions. The elements of the language that give rise to the actions are grammars. Both an FA and a grammar may generate and/or recognize languages (Frank, 2005; Hopcroft & Ullman, 1969).

c. Symbolic Formulation and Description of an FA

Formally, an FA is denoted by a 5-tuple using the symbology:

$M = (Q, \sum, \delta, q_o, F)$, where:

M – Finite state machine

Q – set of states

$\sum$ – alphabet of symbols

q_o – start state

F – set of accept or final states

δ – transition function (Hopcroft & Ullman, 1979).

3. Transition Function

The concept of state transition for the FA can easily be visualized. Consider a "tape" with a sequence of symbols "*x*" from the alphabet ∑ written on it (Hopcroft & Ullman, 1979). A scanning head that reads the symbol as the tape moves causes the machine to adopt the new state as determined by the state prior to the reading of the symbol and the symbol itself. That is, if the FA is in state "*q*" and the symbol "*a*" is scanned and there exists a path to "*p*" from "*q*" given an input of "*a,*" then the resultant state is "*p.*" Symbolically this is:

$$\delta(q, a) = p$$

A compact and functional method for displaying δ is to tabulate it (Hopcroft & Ullman, 1979). The transition function is constructed from three components: the list of states in the leftmost column, the list of inputs in the topmost row excluding the first column and a table of states that reflect the valid transitions for the input and state (read row and column) combinations. The transition function is interpreted by selecting a "from" state in the left-hand column and selecting the state from the intersection of that row and the column matching the next alphabet element from "reading" the input stream. The selected state is the next "from" state. For example, from the δ , as detailed in Table 1, starting in state A and reading an input of 0 will cause the FA to go to state B.

State \ Input	0	1	ε
A	B	C	A
B	D	∅	Z
…	…	…	…

NB: ∅ = no valid transition permitted

Table 1. Example Transition Function
(After Hennie, 1968; Hopcroft & Ullman, 1979)

4. Alphabets

Now, *σ* represents the elements of the alphabet ∑. These elements need not be 0 or 1 as is most commonly used in computing, software and communications applications of FA. They may include various subscripts and other components (Hopcroft and Ullman, 1979). The application and model under development determines the varying degrees of complexity of the various subscripts and associated other components. The inclusion of an element in the alphabet that results in no state transition is the Kleene closure of the alphabet (Hennie, 1968; Hopcroft & Ullman, 1979). The element that results in no state transition when read is ε.

a. Alphabet Elements

An example of the expansion of the elements of the alphabet is as follows, where there is $\sigma \in \Sigma$, and specifically (Hennie, 1968; Hopcroft & Ullman, 1979):

σ (n, ω, κ , P[ ], μ) = input alphabet element, where

n – ID(s) of spacecraft to which the element applies

ω – duration (or distribution) of time spent in current state

κ – arc transition cost vector (power consumption, propulsion)

P[ ] – transition probability matrix for states of inoperability

μ – a vector of mean sojourn times for Inoperable states in P[ ]

This also includes the empty input element ε. Its symbology is:

ε (n, ω, κ, P[ ], μ).

b. Contribution to Network Formulations

Several notable features of this style of alphabet element design and of the transition function assist in the optimization analysis. Firstly, in considering the similarity of the FA to networks, arc costs could be considered as duration of time, power consumption or mass of propulsion expended. Secondly, the n is not limited to a single integer or integer pair but can be a forward star array for complex, i.e., multiple, DSS. Lastly, the inclusion of stochastic terms ω. P[ ], and μ permit a very expansive analysis and exploration of the solution space. This is achieved via NFA where the model is repeatedly run until all the desired state transitions have been enumerated, then transformed into a DFA for analysis (Hennie, 1968; Volpano, 2007). This is beyond the scope of this thesis, yet appears to be a promising field for further investigation.

5. Languages and Grammars

The natural extension is to include a set of symbols from the alphabet rather than an individual symbol (Hopcroft & Ullman, 1979). These sets of symbols or strings of elements from the alphabet are words. Additionally, these words can also be joined together to form sentences or grammar for the FA – thus defining a language. There a several types of languages used in association with FA. These are regular languages (type 3), context-free languages (CFL) (type 2), context-sensitive languages (type 1) and type 0. This is the Chomsky Hierarchy of Languages (Frank, 2005). A formal grammar is a quintuple, G = ($\sum$, Φ, S, R), where:

$\sum$ – alphabet of terminal symbols

Φ – alphabet of non-terminal symbols

S – start symbol

R – set of rules for sequences of symbols (Frank, 2005; Hopcroft & Ullman, 1969).

Therefore, the language of a grammar L(G) or an FA L(M) is the set of strings that can be derived from the start symbol, S, or start state, q_o, according to the description G = ($\sum$, Φ, S, R) or M = (Q, $\sum$, δ, q_o, F). In either case, the protocols that define which transitions are permitted, i.e., the rule set or transition function, factor directly into the language generated by the parent entity (Hennie, 1968). Hence for the case of an FA M, the formal symbolic description is:

$L(M) = \{\xi | \delta(q_o, \xi) \in F\}$, where:

q_o – start state

δ – transition function

F – set of accept or final states

σ – the elements of the alphabet, $\sum$

$\xi \subset \{\sigma\}$ – input strings composed from the elements of the alphabet.

These languages may be defined by regular expressions. As such, there are a number of applicable operations. The set-theoretic operations include union, intersection, difference and compliment. The language-theoretic operations include concatenation, iteration and mirror Image. Regular languages are those defined by the regular operators: union, concatenation and Kleene star. These languages are closed under all above operations except mirror image (Frank, 2005). The language L(M) accepted by the FA M, is a specific set, not just any conglomeration of strings that transpire to be accepted by M (Hopcroft & Ullman, 1979). The language L(M) is not an exhaustive path enumeration, but moreover a prescribed collection of walks.

6. Language Similarities

It is interesting to note that there is an apparent relationship to and between the normal, read 'computer science' or logical machine, constructs of bits, bytes and words as well as the constructs of a language, L(M), generated by the FA M. Table 2 unifies these ideas. In regards to the language, L(M), developed for the DSS and an analysis of the quiddities of it and that used for logical machine reveals the relationships described in the table below. Additionally, the correspondence can be extended further to include some elements of networks.

DSS FA component	Logical Machine equivalent	Network correspondence
Alphabet element	Bit	Arc cost or capacity
Task & meta-task	Byte / word	Shortest path

Table 2. Relationships between FA Components, Logical Machine & Network Concepts, (After Hopcroft & Ullman, 1979)

7. Non-deterministic Finite Automata (NFA)

Non-deterministic finite automata (NFA) are very similar to deterministic finite automata (DFA) or (FA). A primary use is in the proving of theorems. The one factor that separates NFA from FA is that for any same input there can be more than one state transition from any one state—a node without degree greater than one (Hopcroft & Ullman, 1979).

8. Amalgamation of FA

Conglomerations of NFA and/or FA are used to determine if an NFA will accept a given input string (Hopcroft & Ullman, 1979). The NFA may be sequenced consecutively or in parallel with a minimal offset (Hopcroft & Ullman, 1979). The use of NFA could prove very worthwhile for further research into this problem.

9. Reduction and Equivalence

Reducing an overly expanded FA or an NFA down to an equivalent FA produces a more tractable problem. States may also be merged (Carrasco & Oncina, 1994). It also assists in the understanding of the FA (Damiani, 1997; Hennie, 1968). However, not all FA that are produced from NFA have an equivalent or reduced form (Hopcroft & Ullman, 1979).

D. OPTIMIZATION MODELS

Determining the optimization models for DSS modeled in an FA depends upon the particular facet of the FA model under consideration. For the shortest path of a given meta-task of the DSS in terms of state changes, the author enumerates as guided by the transition function. From a different perspective, when determining the minimum length path required for a satellite to process all the targets, the author then models this as a traveling salesman problem. In a similar style, where the object is to maximize the number of targets achieved subject to a finite time period, the author optimizes using the formulation of the prize collecting traveling salesman problem.

1. Network Path Enumeration

Complete enumeration of all paths in a network is often prohibitive in terms of time and memory required. Yet one of the characteristics of an FA is that it can generate the language (read shortest path for a particular meta-task within its design constraints) as specified by the transition function itself. Additionally, during the construction of an FA, it is possible to track the enumerated paths as an integral element of the construction process itself. This feature proves very useful for the models produced in this thesis.

Generally the networks generated from FA will be relatively sparse, whereas NFA will cause a richer linking of nodes in the network due to the nature of the NFA transition function. It is expected that as additional NFA are combined together the connectivity of the resultant network will increase. Further research and analysis would address this concept.

2. Traveling Salesman Problem (TSP)

The TSP in not an unknown problem - in fact, much is written on the nature and description of the problem (Dantzig, Fulkerson and Johnson, 1954; Lawler et al., 1985; Wu, 1992). However, when applying the TSP to a DSS modeled in an FA, the output "path" is an abstraction of the language of the FA.

3. Prize Collecting Traveling Salesman Problem (PCTSP)

As with the TSP, so is the case with PCTSP (Chaves and Lorena, 2005; Gutin and Punnen, 2006).

E. RESEARCH QUESTIONS

The development of the DSS is limited to open source information with constraints of tasks, states, spacecraft, and so on that preclude the model from becoming unmanageable and insurmountable, thus being intractable as an FA.

Each satellite in the DSS has a finite number of states. The limited number of tasks performed dictates these states. The meta-tasks represent the Kleene closure of the alphabet. An analysis of the set of valid state transitions for each meta-task decomposition reveals the optimal schedule and tasking scenario. Exploring the solution space requires the development and evaluation of payoff functions formulated directly from and using the elements of the FA.

1. Specific Research Questions

The specific research questions for this problem predominately contribute to the construction of the FA. In particular, what are the accept states for each

agent in the multi-agent system, what are the meta-tasks and what is the alphabet? Then, constructing a transition function permits the design and explanation of a representational FSA for this problem. Finally, given an indicative sample target set, what is the minimum time for a single spacecraft to process all targets and what is the maximum number of targets that a single spacecraft can process in a time-constrained mission?

2. Potential Research Extensions

Given that this interdisciplinary thesis is largely an explorative venture the pursuit of the research is predominately focused in developing initial concepts. However, discrete event simulations (DES), arising from discrete event graphs, can be mapped to mathematical programming problems (Chan, 2005; Chan & Schruben, 2003, 2005 & 2006), yet there is an apparent dearth of knowledge for such procedures for FSA (Tung & Kleinrock, 1996; Yang et al., 1994). This problem warrants further research in this field. Exploiting the FA/DES duality relationship (Sanchez, 2006) and then applying the extant of modified DES mapping procedures may provide an indirect or heuristic method for the FA formulations. This level of investigation is beyond the scope of this thesis.

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III. THE MODELS

A. MODEL DISCUSSION

The FA models developed in this thesis capture the essential elements and relationships of DSS (Horning, 2006; Ross I.M., 2007). Where actual data is not available, the author approximates values for real world parameters (Ross I.M., 2007).

B. DSS CHARACTERISTICS

In order to develop a preliminary model, a number of assumptions about DSS are required and are discussed below.

1. Orbit Assumptions

The management of orbits is a non-trivial pursuit (Avanzini et al., 2004). Although quaternion-based mathematics is often used (Joly, 1905; Kuipers, 1999), the author adopted a simpler approach. The orbit assumptions include the direction of orbit, orbit deconfliction and other orbit parameters. The direction of orbit is assumed to be anti-clockwise, i.e., the satellite transmits from west to east across the face of the globe. The orbits of multiple satellites are sufficiently out of phase that deconfliction is automatic. In regards to the orbit parameters, not all of the Keplerian elements are used in this simplified model. The orbit parameters for the single spacecraft model are detailed in Table 3.

Parameter	Value
Orbit classification	LEO
Altitude	600 km
Inclination	0°
Period	90 min
Mapping equation for track	y = 62 * cos (x + 45)
Line of sight Horizon	± 135° relative to GCS

Table 3. Single Spacecraft – Orbit Parameters

2. Ground Control Station (GCS)

The GCS for this model is located near Geraldton in Western Australia. This location is chosen because the Australian government recently announced an agreement to host a ground station of the U.S. strategic and military satellite communications system at the Australian Defence Satellite Communications Station in Geraldton (Nelson, 2007). Using (114.63° ¯28.78°) as the latitude and longitude for the GCS, then with data from the table above, the blackout region is between ¯20.38° and ¯110.38° latitude.

3. Communications

It is assumed that the communications between the GCS and spacecraft allow message transmission without interference; in other words, the messages received are the same as those transmitted and vice-versa. This assumption maintains tractability of the models.

4. Transition Probability Matrix

From the details above about the reasons and ephemeral periods of potential inoperability, a state space becomes apparent. Table 4 consolidates and categorizes the inoperable states for all permutations of cause and duration.

	Duration	
Causative Agent	**Temporary**	**Permanent**
Enemy action	Inoperable State 1	Inoperable State 4
Environmental	Inoperable State 2	Inoperable State 5
Reliability	Inoperable State 3	Inoperable State 6

Table 4. Inoperability Transition Probability States

Combing these six inoperable states (INOP n | n $\in$ {1 , … , 6}) with the assumption that except for transitions from an inoperable state to operable state, all other state transitions have the same probability of becoming inoperable, a transition probability matrix is then generated. This is detailed in Table 5.

	To						
From	**State j + 1**	**INOP 1**	**INOP 2**	**INOP 3**	**INOP 4**	**INOP 5**	**INOP 6**
State j	0.9873	0.0005	0.01	0.001	0.0001	0.001	0.0001
INOP 1	0.9768	0.001	0.015	0.005	0.0002	0.0015	0.0005
INOP 2	0.9823	0.001	0.01	0.005	0.0002	0.001	0.0005
INOP 3	0.9768	0.001	0.015	0.005	0.0002	0.0015	0.0005
INOP 4	0	0	0	0	1	0	0
INOP 5	0	0	0	0	0	1	0
INOP 6	0	0	0	0	0	0	1

Table 5. Transition Probability Matrix (**P**) (After Ross & Loomis, 2007)

The inclusion of this matrix in the FA causes the state space for the single spacecraft model to expand to such an extent, via the application of NFA, that it becomes intractable for this analysis. Therefore, only one inoperable state is included in the FA models. Additionally, none of the models developed examine transitions involving the inoperable state. This is an avenue for further research.

C. SINGLE SPACECRAFT FA

Recalling that the symbolic description of an FA is:

$M = (Q, \sum, \delta, q_o, F)$, where:

M – Finite state machine

Q – set of states

$\sum$ – alphabet of symbols

q_o – start state

F – set of accept or final states

δ – transition function, (Hopcroft & Ullman, 1979).

and given that elements of the alphabet may be subscripted or otherwise annotated (Hopcroft & Ullman, 1979), the author defines them as:

$\sigma(n, \omega, \kappa, P[\,], \mu)$ = input alphabet element, where

n – ID of spacecraft to which the element applies

ω – duration (or distribution) of time spent in current state

κ – arc transition cost vector (power consumption, propulsion)

P[ ] – transition probability matrix for states of inoperability

μ – a vector of mean sojourn times for Inoperable states in P[ ]

The author presents the single spacecraft model in Tables 6 to 8 with some interspersed amplifying comments.

1. States (Q)

Table 6 details the states of the single spacecraft model.

Abbreviation	Description
S	Safe
REB	Reboot(ing)
CPC	Collect(ing) Platform Condition
XPC	Transmit(ting) Platform Condition
INOP	Inoperable
T	Transit(ing) to/from target area
R	Reorient(ing) imagery equipment
PTD	Purge Target Data
GTD	Gather Target Data
XTD	Transmit(ting) Target Data
RTD	Relay(ing) Target Data

Table 6. Single Spacecraft FA – States (Q)

2. Alphabet (∑)

The elements σ of the alphabet ∑ are listed in the basal from, void of subscripts and annotations, i.e., the (n, ω, κ, P[ ], μ) components are omitted. Table 7 contains the alphabet for the single spacecraft model.

Alphabet Element (σ)	Description / resultant state
s	GOTO S
b	REB
c	CPC
p	XPC

Alphabet Element (σ)	Description / resultant state
i	INOP
t	T
r	R
d	PTD
g	GTD
x	XTD
q	RTD
ε	No state change for empty input

Table 7. Single Spacecraft FA – Alphabet (∑)

3. Start State (q_o)

$q_o = S$

4. Final States (F)

F = {S, INOP}

5. Transition Function (δ)

The transition function is interpreted by selecting a “from” state in the left-hand column and identifying the “to” state from the intersection of that row and the column matching the alphabet element read in from the input stream. The selected “to” state then becomes the next “from” state and the process is repeated. Table 8 is the transition function for the single spacecraft model.

State \ Input	s	b	c	p	i	t	r	d	g	x	q	ε
S	S	REB	CPC	∅	INOP	T	∅	PTD	∅	XTD	∅	∅
REB	S	∅	CPC	∅	INOP	∅	∅	∅	∅	∅	∅	∅
CPC	S	∅	∅	XPC	INOP	∅	∅	∅	∅	∅	∅	∅
XPC	S	∅	∅	∅	INOP	∅	∅	PTD	∅	∅	∅	∅
INOP	S	∅	∅	∅	INOP	∅	∅	∅	∅	∅	∅	∅
T	S	∅	∅	∅	INOP	∅	R	∅	∅	XTD	∅	∅
R	S	∅	∅	∅	INOP	∅	∅	PTD	∅	∅	∅	∅
PTD	S	∅	∅	∅	INOP	∅	∅	∅	GTD	∅	RTD	∅
GTD	S	∅	∅	∅	INOP	T	∅	∅	∅	XTD	∅	∅
XTD	S	∅	∅	∅	INOP	T	∅	PTD	∅	∅	∅	∅
RTD	S	∅	∅	∅	INOP	∅	∅	PTD	GTD	∅	∅	∅

NB: ∅ = no valid transition permitted

Table 8. Single Spacecraft FA – Transition Function (δ)

D. DUAL SPACECRAFT FA

With two spacecraft, there are now options to employ them for more than individual tasks. In fact, there are several methodologies and consequently the state space (Q) and therefore both the alphabet (∑) and transition function (δ) are considerably larger. This is expected given that the dual spacecraft FA is the result of the combined serial and parallel amalgamation of two smaller FA.

Using an extension of the symbology as described above, for the dual spacecraft FA, one gets the following:

1. States (Q)

This model has two spacecraft. To optimize the length of the state list, the states are subscripted. The subscripts are i, j $\in$ {1, 2}. These subscripts are somewhat associated to but are not directly correlated with the “n” component of the alphabet elements. Table 9 details the states of this model.

Abbreviation	Description
S_i	S/C i: Safe
REB_i	S/C i: Reboot
CPC_i	S/C i: Collect Platform Condition
XPC_i	S/C i: Transmit Platform Condition
$INOP_i$	S/C i: Inoperable
T_i	S/C i: Transit to target area
R_i	S/C i: Reorient imagery equipment
PTD_i	S/C i: Purge Target Data
GTD_i	S/C i: Gather Target Data
XTD_i	S/C i: Transmit Target Data
RTD_i	S/C i: Relay Target Data
$ECL_{i, j}$	Establish communications link between S/C i & j
$LKD_{i, j}$	S/C i & j: linked with S/C i as collector & S/C j as pass-through
PRD_i	S/C i: Purge Re-trans Data
SRD_i	S/C i: Store Re-trans Data
XRD_i	S/C i: Transmit Re-trans Data
RRD_i	S/C i: Relay Re-trans Data

Table 9. Dual Spacecraft FA – States (Q)

2. Alphabet (∑)

The elements σ of the alphabet ∑ are listed in partial basal from, void of most subscripts and annotations, i.e., the (ω, κ, P[ ], μ) components are omitted. For the dual spacecraft model the "n" component is an integer or integer pair as necessary and is included in the list of alphabet elements in Table 10.

Alphabet Element (σ)	**Description / Resultant State**
s(1, …)	S/C 1: GOTO S
b(1, …)	S/C 1: REB
c(1, …)	S/C 1: CPC
p(1, …)	S/C 1: XPC
i(1, …)	S/C 1: INOP
t(1, …)	S/C 1: T
r(1, …)	S/C 1: R
d(1, …)	S/C 1: PTD
g(1, …)	S/C 1: GTD
x(1, …)	S/C 1: XTD
q(1, …)	S/C 1: RTD
ε(1, …)	S/C 1: no state change for empty input
s(2, …)	S/C 2: goto S
b(2, …)	S/C 2: REB
c(2, …)	S/C 2: CPC
p(2, …)	S/C 2: XPC
i(2, …)	S/C 2: INOP

Alphabet Element (σ)	Description / Resultant State
t(2, …)	S/C 2: T
r(2, …)	S/C 2: R
d(2, …)	S/C 2: PTD
g(2, …)	S/C 2: GTD
x(2, …)	S/C 2: XTD
q(2, …)	S/C 2: RTD
ε(2, …)	S/C 2: no state change for empty input
e(1, 2, …)	ECL (S/C 1 & 2)
e(2, 1, …)	ECL (S/C 2 & 1)
l(1, 2, …)	LKD (S/C 1 & 2)
l(2, 1, …)	LKD (S/C 2 & 1)
f(1, …)	S/C 1: PRD
h(1, …)	S/C 1: SRD
y(1, …)	S/C 1: XRD
u(1, …)	S/C 1: RRD
f(2, …)	S/C 2: PRD
h(2, …)	S/C 2: SRD
y(2, …)	S/C 2: XRD
u(2, …)	S/C 2: RRD

Table 10. Dual Spacecraft FA – Alphabet (∑)

3. Start State (q_o)

$q_o = S_i \ \forall i \in \{1, 2\}$

4. Final States (F)

$F = \{S_i, INOP_j\} \ \forall i \neq j \mid i,j \in \{1, 2\}$

5. Transition Function (δ)

The transition function is interpreted in the regular manner. Now for the larger dual spacecraft model, the table has 34 data rows and 36 data columns. Due to its sheer size and supporting tables, it is relegated to Appendix A, however an extract, translated into states and inputs, is detailed in Table 11.

State \ Input	s(1, …)	b(1, …)	c(1, …)	p(1, …)	i(1, …)	t(1, …)
S_1	S_1	REB_1	CPC_1	∅	$INOP_1$	T_1
REB_1	S_1	∅	CPC_1	∅	$INOP_1$	∅
CPC_1	S_1	∅	∅	XPC_1	$INOP_1$	∅
XPC_1	S_1	∅	∅	∅	$INOP_1$	∅
$INOP_1$	S_1	∅	∅	∅	$INOP_1$	∅
T_1	S_1	∅	∅	∅	$INOP_1$	∅
R_1	S_1	∅	∅	∅	$INOP_1$	∅
PTD_1	S_1	∅	∅	∅	$INOP_1$	∅
GTD_1	S_1	∅	∅	∅	$INOP_1$	T_1
XTD_1	S_1	∅	∅	∅	$INOP_1$	∅
RTD_1	S_1	∅	∅	∅	$INOP_1$	∅

NB: ∅ = no valid transition permitted

Table 11. Dual Spacecraft FA – Transition Function (δ) Extract

E. LANGUAGE OF THE MODELS – L(M)

The languages that each of the FA generate are similar. In order to construct the languages L(M), “sentences” are required. These “sentences” are themselves constructed of “words” ξ. Moreover, the “words” are constructed from the elements σ of the alphabets $\sum$ of each of the models as detailed above.

1. Single Spacecraft L(M) Construction

a. Tasks

Using the alphabet for the single spacecraft model above, the author composes the tasks in Table 12.

Description / Task	String
Take no action	{ε}
Interrupt / GOTO Safe	{s}
Become INOP	{i}
Memory Clear	{d, s}
Memory Download	{x}
Status Report	{c, p, s}
Reboot	{b}
Task move	{t, r}
Relay (real-time) Image	{d, q}
Store & Forward (S&F) image	{d, g, t, x}

Table 12. Single Spacecraft FA – Tasks

b. Meta-tasks

Now, the author composes the meta-tasks, i.e., the language L(M), as given by the collection of meta-tasks in Table 13.

Description / Meta-Task	Input “sentence”	Input string
Interrupt / GOTO Safe	{GOTO Safe}	{s}
Become INOP	{INOP}	{i}
Memory Re-set	{Memory download, Memory clear}	{x, d, s}
System Status	{Status report}	{c, p, s}
System Restart	{Reboot, Status report}	{b, c, p, s}
Test Imagery Equipment	{Memory download, Relay Image, S&F image, Memory clear	{x, d, q, d, g, t, x, d, s}
Do orbit repair or adjustment	{Memory download, Task move, Memory clear}	{x, t, r, d, s}
Do relay task	{Task move, Relay image, Memory clear}	{t, r, d, q, d, s}
Do S&F task	{Task move, S&F image, Memory clear}	{t, r, d, g, t, x, d, s}

Table 13. Single Spacecraft FA – Meta-tasks

2. Dual spacecraft L(M) Construction

a. Tasks

Using the alphabet for the dual spacecraft model above, the author composes the tasks in Table 14.

Description	Input
S/C 1: Take no action	{ε(1, …)}
S/C 1: Interrupt / GOTO Safe	{s(1, …)}
S/C 1: Become INOP	{i(1, …)}
S/C 1: Memory Clear	{d(1, …),f(1, …), s(1, …)}
S/C 1: Memory Download	{x(1, …)}
S/C 1: Status Report	{c(1, …), p(1, …), s(1, …)}
S/C 1: Reboot	{b(1, …)}
S/C 1: Task move	{t(1, …), r(1, …)}
S/C 1: Relay (real-time) Image	{d(1, …), q(1, …)}
S/C 1: Store & Forward (S&F) image	{d(1, …), g(1, …), t(1, …), x(1, …)}
S/C 2: Take no action	{ε(2, …)}
S/C 2: Interrupt / GOTO Safe	{s(2, …)}
S/C 2: Become INOP	{i(2, …)}
S/C 2: Memory Clear	{d(2, …), f(2, …), s(2, …)}
S/C 2: Memory Download	{x(2, …)}
S/C 2: Status Report	{c(2, …), p(2, …), s(2, …)}
S/C 2: Reboot	{b(2, …)}
S/C 2: Task move	{t(2, …), r(2, …)}
S/C 2: Relay (real-time) Image	{d(2, …), q(2, …)}

S/C 2: S&F image	{d(2, …), g(2, …), t(2, …), x(2, …)}
S/C 1 & 2: Prep for joint task	{e(1,2, …), l(1,2…)}
S/C 2: Relay (real-time) re-trans data	{f(2, …), u(2…)}
S/C 2: Store re-trans data	{f(2…), h(2…)}
S/C 2: Forward re-trans data	{t(2, …), y(2…)}
S/C 2 & 1: Prep for joint task	{e(2,1, …), l(2,1…)}
S/C 1: Relay (real-time) re-trans data	{f(1, …), u(1…)}
S/C 1: Store re-trans data	{f(1…), h(1…)}
S/C 1: Forward re-trans data	{t(1, …), y(1…)}

Table 14. Dual Spacecraft FA – Tasks

b. Meta-tasks

Now, the author composes the meta-tasks, i.e., the language L(M), as given by the collection of meta-tasks in Table 15. However, only lists one permutation of the joint tasks, as it is trivial to compose the omitted meta-tasks. In the case of joint tasks, the sequence of the spacecraft identifiers has an effect on the operation of the joint task. The protocol adopted for this problem is that the first mentioned spacecraft is the action spacecraft and the second mentioned is the "pass-through" spacecraft. For example, in the "prep for joint task" command, {e(a,b, …)}, where "a" and "b" are the spacecraft identifiers, spacecraft "a" is the one that will be tasked with the imagery collection and spacecraft "b" will be tasked with the sending of the data to the GCS. The expansion of this construction for a larger number of spacecraft is a prime candidate for additional investigation.

Description / Meta-Task	Input "sentence"
S/C 1:	
Interrupt / GOTO Safe	{GOTO Safe}
Become INOP	{INOP}
Memory Re-set	{Memory download, Memory clear}
Status report	{Status report, Memory clear}
Restart System	{Reboot, Status report, Memory clear}
Test Imagery Equipment	{Memory download, Relay Image, S&F image, Memory clear}
Do relay task	{Task move, Relay image, Memory clear}
Do S&F task	{Task move, S&F image, Memory clear}
Do Orbit Repair or Adjust	{Memory download, Task move, Memory clear}

S/C 2:

Interrupt / GOTO Safe	{GOTO Safe}
Become INOP	{INOP}
Memory Re-set	{Memory download, Memory clear}
Status report	{Status report, Memory clear}
Restart System	{Reboot, Status report, Memory Clear}
Test Imagery Equipment	{Memory download, Relay Image, S&F image, Memory clear}
Do relay task	{Task move, Relay image, Memory clear}
Do S&F task	{Task move, S&F image, Memory clear}
Do Orbit Repair or Adjust	{Memory download, Task move, Memory clear}

Joint / Co-operative Tasks:

Do relay/relay task {S/C 1 & 2: Prep for joint task,
S/C 1: Task move,
S/C 2: Task move,
S/C 2: Relay (real-time) re-trans data
S/C 1: Relay image
S/C 1: Memory clear
S/C 2: Memory clear}

Do relay/S&F task {S/C 1 & 2: Prep for joint task,
S/C 1: Task move,
S/C 2: Task move,
S/C 2: Store re-trans data
S/C 1: Relay image
S/C 1: Memory clear
S/C 2: Forward re-trans data
S/C 2: Memory clear}

Do S&F/relay task {S/C 1 & 2: Prep for joint task,
S/C 1: Task move,
S/C 2: Task move,
S/C 1: S&F image
S/C 2: Relay (real-time) re-trans data
S/C 1: Memory clear
S/C 2: Memory clear}

Do S&F/S&F task	{S/C 1 & 2: Prep for joint task, S/C 1: Task move, S/C 2: Task move, S/C 2: Store re-trans data S/C 1: S&F image S/C 1: Memory clear S/C 2: Forward re-trans data S/C 2: Memory clear}
Do Memory Re-set (relay)	{S/C 1 & 2: Prep for joint task, S/C 2: Relay (real-time) re-trans data S/C 1: Memory download (to S/C 2) S/C 1: Memory clear S/C 2: Memory clear}
Do Memory Re-set (S&F)	{S/C 1 & 2: Prep for joint task, S/C 2: Store re-trans data S/C 1: Memory download (to S/C 2) S/C 1: Memory clear S/C 2: Forward re-trans data S/C 2: Memory clear}
Do Status report (relay)	{S/C 1 & 2: Prep for joint task S/C 2: Relay (real-time) re-trans data S/C 1: Status report (to S/C 2) S/C 1: Memory Clear S/C 2: Memory Clear}
Do Status report (S&F)	{S/C 1 & 2: Prep for joint task S/C 2: Store re-trans data S/C 1: Status report (to S/C 2) S/C 1: Memory Clear S/C 2: Forward re-trans data S/C 2: Memory Clear}
Do Reboot (relay)	{S/C 1 & 2: Prep for joint task S/C 2: Relay (real-time) re-trans data S/C 1: Reboot S/C 1: Status report (to S/C 2) S/C 1: Memory Clear S/C 2: Memory Clear}

Do Reboot	{S/C 1 & 2: Prep for joint task
(S&F)	S/C 2: Store re-trans data
	S/C 1: Reboot
	S/C 1: Status report (to S/C 2)
	S/C 1: Memory Clear
	S/C 2: Forward re-trans data
	S/C 2: Memory Clear}
Do Test	{S/C 1 & 2: Prep for joint task
(relay)	S/C 2: Relay (real-time) re-trans data
	S/C 1: Memory Download
	S/C 1: Relay Image
	S/C 1: S&F image
	S/C 1: Memory clear
	S/C 2: Memory clear}
Do Test	{S/C 1 & 2: Prep for joint task
(S&F)	S/C 2: Store re-trans data
	S/C 1: Memory Download
	S/C 1: Relay Image
	S/C 1: S&F image
	S/C 1: Memory clear
	S/C 2: Forward re-trans data
	S/C 2: Memory clear}
Do Orbit Adjust or Repair	{S/C 1 & 2: Prep for joint task
(relay)	S/C 2: Relay re-trans data
	S/C 1: Memory Download
	S/C 1: Task move
	S/C 1: Memory clear}
	S/C 2: Memory clear
Do Orbit Adjust or Repair	{S/C 1 & 2: Prep for joint task
(S&F)	S/C 2: Store re-trans data
	S/C 1: Memory Download
	S/C 2: Forward re-trans data
	S/C 1: Task move
	S/C 1: Memory clear}
	S/C 2: Memory clear

Table 15. Dual Spacecraft FA – Meta-tasks

F. GRAPHICAL REPRESENTATIONS

Both of the FA developed for this problem may be put into a graphical format. This format permits a simple pictorial representation of the FA in which its human readability and comprehension are significantly enhanced. Various other methods exist. These include the MATLAB STATEFLOW and SIMULINK libraries (MATLAB, 2007; Moscinski & Ogonowski, 1995), a statechart representation (Harel, 1987), a graph theory version (Hunt, 2002) and others (Frasconi et al., 1996; Radivojevic & Brewer, 1994). It is recommended that further research into this problem commence with the development of a graphical representation of the FA developed herein.

G. MATLAB

The implementation of the single spacecraft model in MATLAB is a provisional proof of concept. It provides the rudimentary elements of the FA and a clear initiation point for further development (Broadston, 2007). Appendix B details the code for the MATLAB implementation of the single spacecraft model.

IV. TARGETRY OPTIMIZATION

A. TARGETRY MODEL

The model for the targetry consists of eight targets uniformly distributed across the face of the globe. Although the number of targets is only an indicative figure, it is a wholly acceptable point estimate (Ross I.M, 2007). For the purposes of dwell time calculations, the transit times are quantized into 360 1º increments; thus at an altitude of about 600 km with an orbital period of about 90 minutes, 1º of transit by the satellite takes about 15 seconds. Additionally, the dwell times are uniformly distributed between 2 and 60 increments, rounded to the nearest whole number of increments. This equates to a range of dwell times from 30 seconds to 15 minutes. Again, these figures are representative of real-world values (Chien, 2001; Tomme, 2006).

1. Generation of Target Data

Using the random number generator from MS Excel, eight target locations with corresponding dwell times were generated. Considering the nature and criticality of the data set, using the native level of MS Excel random number generation is sufficient for the purposes of this research, yet the limitations of such reliance for robust and demanding simulations are acknowledged (McCullough & Wilson, 1999, 2002 & 2005). The author applied the constraints and guidelines described above to guide and frame the construction of the sample target set. Several short macros written in VBA automated sample target set generation. Table 16 lists a representative version of the data.

Target Id	Lat	Long	Dwell
Target 1	-94.08	76.10	17
Target 2	174.04	-80.72	48
Target 3	68.83	15.58	57
Target 4	-36.08	-43.87	48
Target 5	48.88	7.70	24
Target 6	7.69	74.86	45
Target 7	-167.67	-74.67	17
Target 8	168.15	76.92	34

Table 16. Target Locations and Dwell Times

To grasp a concept of the distribution of the target locations, dwell periods, blackout region, GCS and orbital track, all elements are plotted on a single map of the world in a commonly recognizable projection.

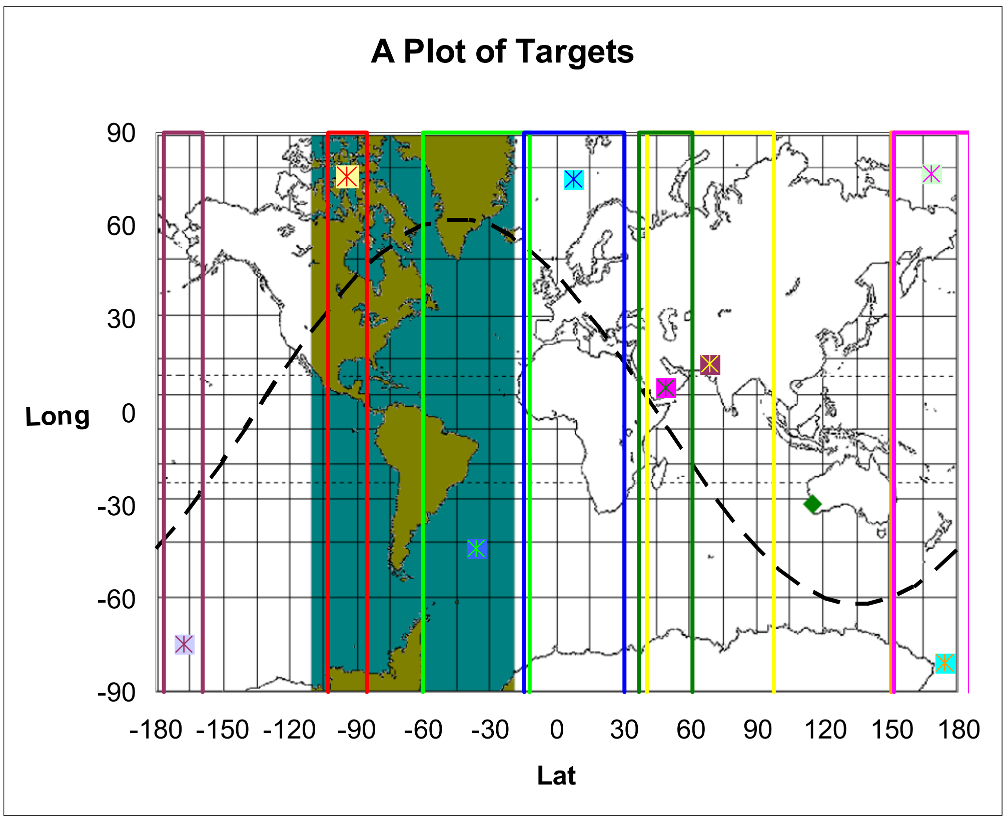

Figure 3. Map of the Earth with Target Locations, Dwell Periods, and Blackout Region

2. Data Preparation

Combining the target data, as detailed above, and the blackout details permitted a complete enumeration of timings from each target to all others. For example, the time for a satellite to travel from the point at which it would ordinarily begin processing target 1 to the end is 17 degrees. This corresponds to the table above where the dwell time for target 1 is also 17 degrees. Likewise, the author calculates all of the other figures in a similar manner where all relevant factors such as, but not exclusively, transit time in the blackout region following the end of imagery storage and overlapping dwell times, are included in the computations as listed in Table 17. These figures translate into the ω components of the elements of the alphabet for the FA.

Dummy	**GMT**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
GMT	0	299.58	198.04	97.33	288.08	60.88	239.81	373.17	185.15
T1	94.42	17	283.62	182.91	433.5	146.46	475.77	286.42	270.73
T2	161.96	76.38	48	259.29	149.87	222.84	192.15	2.79	347.1
T3	262.67	177.09	100.71	57	250.59	323.55	292.86	103.5	87.82
T4	167.92	286.5	210.13	109.41	48	72.97	402.27	212.92	197.23
T5	299.12	213.54	137.16	396.45	287.03	24	329.31	139.95	124.26
T6	329.81	244.23	167.85	67.14	317.73	30.69	45	170.64	154.95
T7	20.83	73.58	357.21	256.5	147.08	220.05	189.36	17	344.31
T8	174.85	89.27	372.9	272.18	162.77	235.74	205.05	15.69	34

Table 17. Prepared Data for Commercial Off-the-shelf Optimization Software

B. FORMULATIONS

Given that the two problems are from related classes of optimization problems, it is expected that the formulations would be similar – and they are. However, some subtle differences permit significantly different analyses of the problem.

1. TSP Formulation

The TSP formulation is:

INDICES

$i, j \in \{0, \cdots, I\}$	target identifier, including startpoint as $i, j = 0$
$k \in \{1, \cdots, K\}$	leg identifier

DATA [UNITS]

$time_{i,j}$	duration of leg from i to j [time]

DECISION VARIABLES [UNITS]

$X_{i,j,k}$	a binary varialble with value one only if the satellite travels from i to j during leg k [dimensionless]

FORMULATION

minimize $\sum_{i,j,k} time_{i,j} X_{i,j,k}$

s.t.	$X_{i,j,k}$	$=0$	$\forall\ i=j$	(1.1)
	$X_{i,j,k}$	$=0$	$\forall\ j=0$	(1.2)
	$\sum_{j,k} X_{j,i,k}$	≤ 1	$\forall\ i$	(1.3)
	$\sum_{j,k} X_{i,j,k}$	≤ 1	$\forall\ i$	(1.4)
	$\sum_{i,j} X_{j,i,k}$	≤ 1	$\forall\ k$	(1.5)
	$\sum_{j} X_{i,j,1}$	$=1$	$\forall\ j, i=0$	(1.6)
	$X_{i,j,1}$	$=0$	$\forall\ j, i\neq 0$	(1.7)
	$\sum_{j} X_{j,i,k}$	$=\sum_{j} X_{i,j,k+1}$	$\forall\ i, k<K$	(1.8)
	$X_{j,i,k}$	binary	$\forall\ i,j,k$	(1.9)

DISCUSSION

The objective of the TSP formulation is to minimize the total time required to visit each target once. Constraint 1.1 prevents the direct repetition of any targets and constraint 1.2 ensures that the start point is not considered a target. Constraints 1.3, 1.4 and 1.5 ensure that entry into and departure from each node occurs at most once and that each leg is used at most once. The initial conditions for the problem are given by constraints 1.6 and 1.7, with constraint 1.8 ensuring that a distinct path through all the targets is generated. Finally, constraint 1.9 defines the decision variables.

2. PCTSP Formulation

The PCTSP formulation is:

INDICES

$i, j \in \{0,\cdots,I\}$	target identifier, including startpoint as $i, j=0$
$k \in \{1,\cdots,K\}$	leg identifier

DATA [UNITS]

$time_{i,j}$ duration of leg from i to j [time]

$timeLimit$ upper bound on time available to visit targets [time]

DECISION VARIABLES [UNITS]

$X_{i,j,k}$ a binary varialble with value one only if the satellite travels from i to j during leg k [dimensionless]

FORMULATION

$$\text{maximize} \quad \sum_{i,j,k} X_{i,j,k}$$

$$s.t. \quad X_{i,j,k} = 0 \quad \forall\, i = j \qquad (2.1)$$

$$X_{i,j,k} = 0 \quad \forall\, j = 0 \qquad (2.2)$$

$$\sum_{j,k} X_{j,i,k} \le 1 \quad \forall\, i \qquad (2.3)$$

$$\sum_{j,k} X_{i,j,k} \le 1 \quad \forall\, i \qquad (2.4)$$

$$\sum_{i,j} X_{j,i,k} \le 1 \quad \forall\, k \qquad (2.5)$$

$$\sum_{j} X_{i,j,1} = 1 \quad \forall\, j, i = 0 \qquad (2.6)$$

$$X_{i,j,1} = 0 \quad \forall\, j, i \ne 0 \qquad (2.7)$$

$$\sum_{j} X_{j,i,k} \ge \sum_{j} X_{i,j,k+1} \quad \forall\, i, k < K \qquad (2.8)$$

$$X_{j,i,k} \ \text{binary} \quad \forall\, i, j, k \qquad (2.9)$$

$$\sum_{i,j,k} time_{i,j} X_{i,j,k} \le timeLimit \qquad (2.10)$$

DISCUSSION

The objective of the PCTSP formulation is to maximize the number of unique targets visited in a set amount of time. The first difference in the constraints of the TSP and PCTSP formulations is the relaxation of constraint 2.8 - now it does not force the generation of a path that visits all nodes. The other difference is the additional constraint, 2.10, which sets the upper bound on the time available for the spacecraft to visit all targets.

C. RESULTS

The author implemented the TSP and PCTSP formulations in GAMS (GAMS, 2007). Each formulation took less than a second to solve via CPLEX for every sample target set generated using the rudiments previously described, including those in Table 17. The TSP scenario has 91 constraints and 456 variables. The PCTSP has one extra constraint and the same number of variables.

1. TSP Results

For the sample target set in the table above, the optimal target processing sequence for a satellite beginning its orbit at GMT is:

6, 5, 8, 4, 3, 2, 7, 1.

The minimum time required is 2.34 orbits. From other sample target sets, the minimum times are similar.

2. PCTSP Results

For the sample target set in the table above, the optimal target processing sequence for a satellite beginning a time constrained orbit at GMT is:

5, 8, 4, 3, 2, 7, 1.

The maximum number of targets processed in two orbits is seven. From other sample target sets, the maximum number of targets ranged from five to eight. Reducing the minimum time to one orbit gave a commensurate reduction in the number of targets.

3. Discussion

The process for generating optimal target selection sequences for artificial yet realistically representative target sets is relatively simple when using the TSP and PCTSP formulations. With further research to include modification of the

GAMS code and the input data files it is possible generate all the FA inputs, in the correct sequence, for the entire mission as part of the optimization procedure. Additional research and analysis is required to determine how or even if these or equivalent formulations or processes could be achieved using just the elements of the FA.

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

Satellite systems can indeed be modeled using FA. It is considered that the fidelity of the models produced in the thesis is sufficient, yet for more in-depth research additional detailed models are needed to provide a wider scope for analysis and exploration of the field. Regardless, the benefits of FA are that they are simple without being simplistic yet at the same time permit a wide variety of factors to be included in the model. In order to effectively construct an FA, there is a considerable amount of knowledge of the system to be modeled that must be brought together and understood. In particular, the state space, transition function and language need clear and unambiguous definitions. For the multiple spacecraft system the task becomes more complex as various interactions also need to be either permitted and expressible or prohibited by the model.

However, by using clearly defined specific assumptions and indicative values these preliminary models maintain tractability. Additionally, there is a very broad foundation from which to pursue further analysis and development of the models in the thesis. The exploration of the growth of more complex models and optimization classifications beyond the TSP and the PCTSP formulations are indicative of some areas for further research.

B. RECOMMENDATIONS

In terms of the research done in this thesis and the concluding comments, the author presents the following recommendations for further research and analysis. The application of FA to other problems is also acknowledged as a worthy endeavor.

1. Graphical Representations

A graphical representation of an FA often provides insight to the reader that is not normally evident via an equivalent cursory reading of the details and specifications of the FA. Taking the two FA described herein and constructing a graphical representation could very well highlight additional aspects of the multiple satellite system that are not presently obvious. It is recommended that any extension of this research commence with the production of graphical representations of the FA presented herein.

2. More Spacecraft in the Model

The addition of more spacecraft to the model would increase the realism and complexity of the FA. In addition, with the appropriate management of the state space and other elements of the FA the model could be developed along a similar process used for this problem. A constellation of about five spacecraft would represent a suitable system. Special attention is needed for the construction and clarification of joint tasks. It is recommended that additional spacecraft be added to this model along with the production of explicit instructions, rule sets or constraints to govern the generation, proliferation and management of joint tasks (Kang, Sparks & Banda, 2000 & 2001).

3. NFA

Beyond the additional spacecraft, an application of NFA or possibly even the development of a collection of smaller FA could also prove useful in modeling the various failure modalities faced by satellite systems. This could also be combined with some stochastic Markovian analysis and modeling. It is recommended that extensions of this research that investigate the effects of failures on the optimization of tasking and scheduling encompass a combination of stochastic Markovian procedures and NFA.

4. PDA

In progressing to a “smart” satellite system where the individual spacecraft have the capability for task storage and retrieval and other functions, there is scope for the employment of PDA. It is recommended that this be investigated as an individual problem or in concert with the others describe above.

5. Integer Linear Programming (ILP) Relationship to FA

Finally, given a functional FA, as arisen from the recommendations above, it requires a much more thorough and in-depth analysis of the processes to transform the FA into an ILP and the relationships between the two constructs than that delivered by this thesis. This could address such issues as the developing of heuristics or other novel solutions to resolving conflicting tasking and scheduling of multiple satellite systems. It is recommended that a comprehensive examination of the processes and procedures to transform an FA into an ILP and the relationships between the two constructs be undertaken. Additionally, it is recommended that the modification of the commercial off-the-shelf optimization software input files be explored so that its output would also generate all the FA inputs, in the correct sequence, for the entire optimized mission (Kam, 1996; Kang & Sparks, 2003).

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APPENDIX A. Dual Spacecraft FA – Transition Function (δ)

To simplify the transition function for display in this document, the author maps both the state space and the alphabet to integer values. This also assists with an implementation in MATLAB. Table 18 details the state space mapping.

State	Mapped Value
S,(1)	1
REB,(1)	2
CPC,(1)	3
XPC,(1)	4
INOP,(1)	5
T,(1)	6
R,(1)	7
PTD,(1)	8
GTD,(1)	9
XTD,(1)	10
RTD,(1)	11
S,(2)	12
REB,(2)	13
CPC,(2)	14
XPC,(2)	15
INOP,(2)	16
T,(2)	17
R,(2)	18
PTD,(2)	19
GTD,(2)	20
XTD,(2)	21
RTD,(2)	22
ECL,(1,2)	23
ECL,(2,1)	24
LKD,(1, 2)	25
LKD,(2, 1)	26
PRD,(1)	27
SRD,(1)	28
XRD,(1)	29
RRD,(1)	30
PRD,(2)	31
SRD,(2)	32
XRD,(2)	33
RRD,(2)	34

Table 18. Dual Spacecraft FA – State to Value Mapping

Table 19 details the input element/alphabet mapping.

Input description	Alphabet Element (σ)	Mapped Value
S/C # 1: GOTO Safe	s(1, …)	1
S/C # 1: do Reboot	b(1, …)	2
S/C # 1: Collect P/f Cond	c(1, …)	3
S/C # 1: X-mit P/f Cond	p(1, …)	4
S/C # 1: become Inoperable	i(1, …)	5
S/C # 1: do Transit	t(1, …)	6
S/C # 1: do Re-orient	r(1, …)	7
S/C # 1: Purge Target Data	d(1, …)	8
S/C # 1: Gather Target Data	g(1, …)	9
S/C # 1: X-mit Target Data	x(1, …)	10
S/C # 1: Relay Target Data	q(1, …)	11
S/C # 1: empty input	ε(1, …)	12
S/C # 2: GOTO Safe	s(2, …)	13
S/C # 2: do Reboot	b(2, …)	14
S/C # 2: Collect P/f Cond	c(2, …)	15
S/C # 2: X-mit P/f Cond	p(2, …)	16
S/C # 2: become Inoperable	i(2, …)	17
S/C # 2: do Transit	t(2, …)	18
S/C # 2: do Re-orient	r(2, …)	19
S/C # 2: Purge Target Data	d(2, …)	20
S/C # 2: Gather Target Data	g(2, …)	21
S/C # 2: X-mit Target Data	x(2, …)	22
S/C # 2: Relay Target Data	q(2, …)	23
S/C # 2: empty input	ε(2, …)	24
S/C # 1 to S/C # 2: Estab Comms Link	e(1, 2, …)	25
S/C # 2 to S/C # 1: Estab Comms Link	e(2, 1, …)	26
S/C # 1 & S/C # 2: Linked for Comms	l(1, 2, …)	27
S/C # 2 & S/C # 1: Linked for Comms	l(2, 1, …)	28
S/C # 1: Purge Re-trans Data	f(1, …)	29
S/C # 1: Store Re-trans Data	h(1, …)	30
S/C # 1: Forward Re-trans Data	y(1, …)	31
S/C # 1: Relay Re-trans Data	u(1, …)	32
S/C # 2: Purge Re-trans Data	f(2, …)	33
S/C # 2: Store Re-trans Data	h(2, …)	34
S/C # 2: Forward Re-trans Data	y(2, …)	35
S/C # 2: Relay Re-trans Data	u(2, …)	36

Table 19. Dual Spacecraft FA – Alphabet to Value Mapping

Tables 20 and 21 taken together form the transition function for the dual spacecraft model.

Mapped States	Mapped Inputs																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	1	2	3		5	6				10								17
2	1		3		5													
3	1			4	5													
4	1				5			8										
5	1				5													
6	1				5		7											
7	1				5			8		10								17
8	1				5				9		11							
9	1				5	6				10								
10	1				5	6		8			11							
11	1				5			8	9									
12						6		8					12	13	14		16	17
13													12		14		16	
14													12			15	16	
15													12				16	
16													12				16	
17													12				16	
18						6							12				16	
19													12				16	
20													12				16	17
21								8					12				16	17
22													12				16	
23	1				5													
24													12				16	
25	1				5	6							12					
26	1												12				16	17
27	1				5													
28	1				5										14			
29	1				5	6		8										
30	1				5									13	14			
31													12				16	
32		2	3					8		10			12				16	
33													12				16	
34		2	3					8		10			12				16	

Table 20. Dual Spacecraft FA – Transition Function (part 1 of 2)

Mapped States	Mapped Inputs																	
	19	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
1		19					23	24									33	
2																		
3																		
4																		
5																		
6																		
7											27							
8											27		29					
9																		
10		19															33	
11																		
12				21			23	24					29					
13																		
14																		
15		19																
16																		
17	18																33	
18		19		21											31			
19			20		22										31			
20				21														
21		19			22								29					
22		19																
23									25									
24										26								
25															31			
26											27							
27												28		30				
28		19		21														
29																		
30		19		21														
31																32		34
32																		
33		19																
34																		

Table 21. Dual Spacecraft FA – Transition Function (part 2 of 2)

Despite the mapping of the state space and alphabet to integers, the process to step through the transition function and the three-part construction of the table, as previously described, remain extant.

APPENDIX B. MATLAB Code for Single Spacecraft FA

This MATLAB code demonstrates the basic formulation of the single spacecraft model using previously defined FA elements and presents a method to enumerate the FA state changes as dictated by an input string.

```
% MAJ B.N. Laboo - MSOR Thesis Code, Apr 2007
% with assistance from Mr. Bob Broadston
%
clear all
clc

Q = {                                              % state space
[1], ['S'], ['Safe']
[2], ['REB'], ['Reboot']
[3], ['CPC'], ['Collect P/f Cond']
[4], ['XPC'], ['X-mit P/f Cond']
[5], ['INOP'], ['Inoperable']
[6], ['T'], ['Transit']
[7], ['R'], ['Re-orient']
[8], ['PTD'], ['Purge Target Data']
[9], ['GTD'], ['Gather Target Data']
[10], ['XTD'], ['X-mit Target Data']
[11], ['RTD'], ['Relay Target Data']};

lcSigma = {                                        % alphabet elements
[1], ['s'], [1, 1], [1], ['GOTO Safe']
[2], ['b'], [1, 1], [1], ['do Reboot']
[3], ['c'], [1, 1], [1], ['Collect P/f Cond']
[4], ['p'], [1, 1], [1], ['X-mit P/f Cond']
[5], ['i'], [1, 1], [1], ['become Inoperable']
[6], ['t'], [1, 1], [1], ['do Transit']
[7], ['r'], [1, 1], [1], ['do Re-orient']
[8], ['d'], [1, 1], [1], ['Purge Target Data']
[9], ['g'], [1, 1], [1], ['Gather Target Data']
[10], ['x'], [1, 1], [1], ['X-mit Target Data']
[11], ['q'], [1, 1], [1], ['Relay Target Data']
[12], ['z'], [1, 1], [0], ['empty input']};

delta = [                                          % transition function
1,2,3,0,5,6,0,8,0,10,0,0;
1,0,3,0,5,0,0,0,0,0,0,0;
1,0,0,4,5,0,0,0,0,0,0,0;
1,0,0,0,5,0,0,8,0,0,0,0;
1,0,0,0,5,0,0,0,0,0,0,0;
1,0,0,0,5,0,7,0,0,10,0,0;
1,0,0,0,5,0,0,8,0,0,0,0;
1,0,0,0,5,0,0,0,9,0,11,0;
1,0,0,0,5,6,0,0,0,10,0,0;
1,0,0,0,5,6,0,8,0,0,0,0;
1,0,0,0,5,0,0,8,9,0,0,0];
```

```
q_0 = {[1], ['S'], ['Safe']};                                % start state

F = {[1], ['S'], ['Safe'];[5],['INOP'],['Inoperable']};      % final states

LofM = {                                                     % meta-tasks
[1], ['s'], ['GOTO Safe']
[5], ['i'], ['become Inoperable']
[10,8,1], ['x',' ','d',' ','s' ], ['Memory Reset']
[3,4,1], ['c',' ','p',' ','s'], ['System Status']
[2,3,4,1], ['b',' ','c',' ','p',' ','s'], ['System Reboot']
[10,8,11,8,9,10,8,1], ['x',' ','d',' ','q',' ','d',' ','g',' ','t', ...
' ','x',' ','d',' ','s' ], ['Test Img Equip']
[10,6,7,8,1], ['x',' ','t',' ','r',' ','d',' ','s'], ...
['Orbit Ops'] %['Adjust or Repair Orbit']
[6,7,8,11,8,1], ['t',' ','r',' ','d',' ','q',' ','d',' ','s'], ...
['Do Relay Task']
[6,7,8,9,10,8,1], ['t',' ','r',' ','d',' ','g',' ','t',' ','x',' ', ...
'd',' ','s'], ['Do S&F Task']};

%======================================================================

[a,b]=size(LofM);
results = cell(a+1,4); % define empty array for data capture
results{1,1} = ['Meta-task'];
results{1,2} = ['State path'];
results{1,3} = ['Input string'];
results{1,4} = ['Length'];
for counter =  1:1:a; % for each meta-task
    comd_vec =  LofM{count er,1};% set comd vector = meta-task comd vector
    nextState = 0; % initialize nextState
    startState = 1; %initialize startState to "safe"
    results{counter+1,2} = Q{startState,2}; % initialize state path to “S”
    results{counter+1,4} = 0; %initialize path length to 0
    [c,d] = size(comd_vec);
    results{counter+1,1} = LofM{counter,b}(1,:);
        % record Meta-task
    for index  = 1:1:d; % for each input in the comd vector
        nextState = delta(startState, comd_vec(index)); %do state change
        results{counter+1,2} = cat(2, results{counter+1,2}, ' ', ...
            Q{nextState,2});
                % keep track of the state path
        results{counter+1,3} = cat(2, results{counter+1,3}, ' ', ...
            lcSigma{nextState,2}(1,1));
                % keep track of the inputs
        results{counter+1,4} = results{counter+1,4} + ...
            lcSigma{startState, 4}(1,1);
                % increment pathlength
        startState = nextState;
    end
end
results     % display all results
```

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